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FINAL REPORT-SUMMARY OF RESEARCH
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TITLE: Geology of Lunar Landing Sites and Origin of Basin Ejecta from a Clementine Perspective

PRINCIPAL INVESTIGATOR: Bradley L. Jolliff
Department of Earth & Planetary Sciences
Campus Box 1169
Washington University
One Brookings Drive
St. Louis, MO 63130-4899

CO-INVESTIGATOR: Larry A. Haskin

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Overview

The goals of this research were to examine Clementine multispectral data covering the Apollo landing sites in order to (1) provide ground truth for the remotely sensed observations, (2) extend our understanding of the Apollo landing sites to the surrounding regions using the empirically calibrated Clementine data, and (3) investigate the composition and distribution of impact-basin ejecta using constraints based upon the remotely sensed data and the Apollo samples. Our initial efforts (in collaboration with P. Lucey and coworkers) to use the Apollo soil compositions to “calibrate” information derived from the remotely sensed data resulted in two extremely useful algorithms for computing estimates of the concentrations of FeO and TiO₂ from the UV-VIS 5-band data (Blewett et al., 1997a-c). In this effort, we used the average surface soil compositions from 37 individual Apollo and 3 Luna sample stations that could be resolved using the Clementine data. We followed this work with a detailed investigation of the Apollo 17 landing site, where the sampling traverses were extensive and the spectral and compositional contrast between different soils covers a wide range (Jolliff, 1998a,b). We have begun to investigate the nature and composition of basin ejecta by comparing the thick deposits on the rim of Imbrium in the vicinity of the Apollo 15 site and those occurring southeast of the Serenitatis basin, in the Apollo 17 region. We continue this work under NAG5-6784, “Composition, Lithology, and Heterogeneity of the lunar crust using remote sensing of impact-basin uplift structures and ejecta as probes.”

The main results of our work are given in the following brief summaries of major tasks. Detailed accounts of these results are given in the attached papers, manuscripts, and extended abstracts.

Apollo landing sites as ground truth for remotely sensed observations

The five-band UV-VIS data collected by the 1994 Clementine mission have proven to be very useful because they were obtained at a relatively high resolution (100–200 m), cover nearly the entire globe, and provide a means to estimate the iron and titanium contents of lunar soils. Knowledge of the distribution and concentration of these two elements is tantamount to interpretations of the geological history and resource potential of the lunar surface.

A relationship between the 750 nm reflectance and the 950/750 ratio, which is a measure of the ferrous-iron absorption band, was exploited by Lucey and coworkers to estimate the abundance of ferrous iron in soils sensed remotely by the Clementine spacecraft. Similarly, the slope of spectra from 415 nm to 750 nm serves as a relative measure of the titanium oxide content. We collaborated with Lucey’s group to use Apollo and Luna landing-site soil compositions to provide an empirical calibration for both of these relationships. Jolliff and coworkers combined landing site geology and their extensive database of soil

compositions to determine the appropriate sample stations and surface soil compositions for correlation to individual pixels and small groups of pixels in the UV-VIS images of the landing sites. Blewett and Jolliff selected 40 individual sampling stations for this correlation, and provided a calibration that has been used by many researchers to investigate the FeO and TiO₂ concentrations of specific geologic units all over the Moon's surface (Blewett et al., 1997a-c; Jolliff, 1997a,b).

Jolliff (1997a,b, 1998a,b) extended the initial study of Blewett et al. by investigating in detail the variations in spectral parameters among twenty Apollo 17 sample stations. This investigation included parameters used to distinguish mafic-silicate mineralogy, pyroclastic-glass concentrations, soil maturity, lighting conditions (photometry) related to local slopes, and uncertainties related to mosaicing adjacent strips of data taken during different orbits, at different altitudes, and under different pointing and illumination geometries. This work was necessary in order to place some constraints on the accuracy of compositional estimates based on the UV-VIS data.

Concentrations of FeO and TiO₂, in combination, are used to distinguish the major lunar rock types including anorthosite, which is abundant in the lunar crust; more mafic olivine- and pyroxene-bearing rocks such as norite and troctolite that represent igneous intrusives; impact-melt rocks that represent basin ejecta from deep in the Moon's crust; and lunar mare basalts, which are very high in FeO and highly variable in TiO₂ content. Large areas of the Moon's surface that show coherent patterns in their FeO and TiO₂ contents delineate several major terranes that relate to the early geologic history of the Moon, which was obscured by the heavy bombardment and basin formation that occurred some 4 billion years ago. Concentrations of FeO and TiO₂ from expansive geological units at the Moon's surface, determined from the Clementine data, are now being compared to the Lunar Prospector gamma-ray data (resolution of ~ 150 km squares) and will be used to extend those important new data to high resolution.

Extend knowledge of the Apollo sites to surrounding regions using empirically calibrated Clementine data

Among the materials collected at the Apollo 17 landing site, three major classes of rocks were found. These include the Ti-rich basalts of the Taurus-Littrow valley, the massive, mafic impact-melt breccias that occur as boulders at the site and large outcrops of rock on the highland massif slopes, and the feldspathic breccias that make up the rest of the highland deposits. From geological relationships at the landing site, we can infer where in the local area each of the rock types comes from. Then, by knowing how the soils that are made up of these components appear spectrally, we can characterize the surrounding regions in terms of their spectra. Thus we can determine whether other geologic formations are composed of rock components similar to those at the Apollo 17 site, and in what approximate proportions, or whether different rock types must also be present to explain the spectra.

As an example, at the Apollo 17 site, we found small fragments of a very-low Ti basalt, thrown there by large meteorite impacts (Jolliff et al., 1996), but we previously did not know where they came from. However, from the Clementine data, we have identified regions of nearby elevated plains that have FeO too high and TiO₂ too low to be explained as any combination of the known major rock types from the Apollo 17 site (Jolliff, 1998a). We conclude from the morphology of these deposits and from their inferred compositions that they are products of ancient volcanism that may predate the large basin impacts.

As another example, we devised a test to try to distinguish compositionally the presence of secondary material thrown in from rays of ejecta from the ~100 million year old crater Tycho. We examined the Clementine spectra for soils where rays appear to cross the Apollo 17 landing site, and we searched the soils from those sample stations to look for unusual geological components. We identified a set of ferroan granulitic breccias and troctolitic fragments whose compositions and mineralogy are consistent with spectroscopic data from the rocks exposed in the central peaks and ejecta of Tycho, but which are uncommon in most Apollo 17 soils (Jolliff et al., 1998). Although we can not be absolutely sure these are

Tycho components, this method of sorting out the provenance of specific regolith deposits in areas where there is significant spectral contrast has great promise and will continue to be used by us and others.

Composition and distribution of basin ejecta: constraints based on remotely sensed data and Apollo samples

From the chemical compositions of impact-melt breccias collected from the Apollo sites and from the Apollo orbital gamma-ray data for thorium, Haskin (1997a,b) deduced that an area of the Moon's surface, roughly oval in shape and characterized by an enrichment in the element Th and other incompatible elements, occurred in the vicinity of the Procellarum and Imbrium regions. The Imbrium impact, which was the last of the great basin impacts on the nearside of the Moon, apparently struck a pre-existing, compositionally enriched terrane and distributed Th-rich, impact-melt-bearing ejecta over much of the Moon. Thus, contrary to previous interpretations that held to the notion that each of the large basin impacts in turn excavated mafic, Th-rich material from deep in the crust, this new interpretation implies a tremendous enrichment and localization of the heat-producing radionuclides (Th, U, K). Such a condition would have important implications for the early evolution of the Moon's crust and mantle and for many of the rocks collected by the Apollo missions that have been taken to be typical of the lunar crust. This hypothesis, if correct, might mean that many of the Apollo rocks are not typical of the crust as a whole, but are the specialized products of this unusual geochemical terrane.

We have begun to test this hypothesis by investigating the chemical compositions of large deposits of ejecta as estimated from the Clementine UV-VIS data. We have coupled this with modeling of the depths and proportions of such ejecta expected to occur at different distances from the center of Imbrium (Moss et al., 1998; Jolliff and Haskin, 1998; Haskin and Jolliff, 1998). We found that for many highland regions around the globe, the Th concentrations are consistent with mixing of Th-rich ejecta from Imbrium with Th-poor local regolith substrates. However, using Clementine-derived variations in FeO concentrations of ejecta related to distance from the Imbrium and Serenitatis basins, it appears that the Th-rich signal at the southeastern rim of the Serenitatis basin results mainly from the ejecta of that basin, and not Imbrium alone. Thus, it appears that the Serenitatis impact event also dug into the Th-enriched crustal terrane at depth. The likelihood of this scenario was strengthened by the recent map of Th determined by the Lunar Prospector mission that showed the Serenitatis basin to be at the edge of the Th-enriched terrane.

Our results are also consistent with the geophysically anomalous nature of the basin (Wieczorek et al., 1998). We continue to test models of the structure of the lunar crust as revealed by the composition of ejecta exhumed by the large basin impact events. Our early work with the Clementine data have placed us in a position to exploit the Clementine data to their fullest potential and to integrate results based on those data with results emerging from the currently in-progress Lunar Prospector mission.

New Views of the Moon...

Our work with the Clementine UV-VIS data set has led directly to our involvement in a new lunar science initiative entitled "*New Views of the Moon: Combined Remotely Sensed and Lunar Sample Data Sets*," begun by CAPTEM (Curation and Analysis Planning Team for Extraterrestrial Materials) and co-chaired by Jolliff and G. Ryder on behalf of CAPTEM. This initiative has as one of its main objectives to use multidisciplinary approaches that incorporate the constraints and results of the different global, remotely sensed data sets and the Apollo samples. The first initiative activity was a special session at the 29th Lunar and Planetary Science Conference entitled "*Probing the Moon with Remote Sensing and Samples: A New Integration*," co-chaired by Jolliff. A second activity was a workshop entitled "*New Views of the Moon: Integrated Remotely Sensed, Geophysical, and Sample Datasets*," which was held at the Lunar and Planetary Institute Sept. 18–20, 1998, with Jolliff as one of the organizers and co-convenors.

Among the themes that emerged from the workshop was that the Moon's present-day distribution of materials at the surface reflects a globally asymmetric early differentiation, which left a unique mafic geochemical province rich in trace elements beneath the Imbrium-Procellarum region (the High-Th Oval

Region of Haskin, 1997b). Although the early igneous crust of the Moon was constantly pounded by impacting planetary debris, the next to last of the major, basin-forming events, the Imbrium event, excavated Th-rich material from the High-Th Oval Region and spread it Moon-wide. Our work to date using the Clementine and other remotely sensed data, along with constraints provided by the Apollo samples, is reforming our views of just how the early Moon formed and how its materials and resources are distributed about the surface today. We are continuing this important work under the support of the NASA Cosmochemistry and Planetary Geology & Geophysics Programs.

PUBLICATIONS RELATED TO GRANT

(attached unless indicated otherwise)

Papers published, in press, or submitted 1996–1998

- Blewett D. T., Lucey P. G., Hawke B. R., and Jolliff B. L. (1997c) Clementine images of the lunar sample-return stations: Refinement of FeO and TiO₂ mapping techniques. *Journal of Geophysical Research* **102**, 16,319–16,325.
- Haskin L. A. (1998) The Imbrium impact event and the thorium distribution at the lunar highlands surface. *Journal of Geophysical Research* **103**, 1679–1689.
- Haskin L. A., Korotev R. L., Rockow K.M., and Jolliff B. L. (1998) The case for an Imbrium origin of the Apollo Th-rich impact-melt breccias. *Meteoritics and Planetary Science*, April 1998, in press [not attached].
- Jolliff B. L., Rockow K. M., Korotev R. L., and Haskin L. A. (1996a) Lithologic distribution and geologic history of the Apollo 17 site: The record in soils and small rock particles from the highlands massifs. *Meteoritics and Planetary Science* **31**, 116–145.
- Jolliff B. L. (1998a) Clementine UV-VIS multispectral data and the Apollo 17 landing site: What can we tell and how well? *Journal of Geophysical Research*, submitted, reviewed, in revision.
- Moss B. E., Haskin L. A., and McKinnon W. B. (1998) On estimating ejecta deposit thicknesses and proportions of materials from distant basins at lunar highlands sites. *Meteoritics and Planetary Science*, submitted - in revision [not attached].

Abstracts (1996–1998)

- Blewett D. T., Lucey P. G., Hawke B. R., and Jolliff B. L. (1997a) Clementine images of the lunar sample-return stations: Improvements to the TiO₂ mapping technique. *Lunar and Planetary Science* **XXVIII**, 119–120.
- Blewett D. T., Lucey P. G., Hawke B. R., and Jolliff B. L. (1997b) FeO mapping of the Moon: Refinement using images of the sample-return stations. *Lunar and Planetary Science* **XXVIII**, 121–122.
- Haskin L. A. and McKinnon W. B. (1996) Could Imbrium ejecta be the source of the high-Th material in the Van De Graaff region of the Moon? *Lunar and Planetary Science* **XXVII**, 501–502 [not attached].
- Haskin L. A. (1997a) The distribution of Th on the Moon's surface. *Lunar and Planetary Science* **XXVIII**, 519–520.
- Haskin L. A. (1997b) The high-Th oval region of the Moon. *Lunar and Planetary Science* **XXVIII**, 521–522.

- Haskin L. A. and Jolliff B. L. (1998) On estimating provenances of lunar highland materials. In *New Views of the Moon: Integrated Remotely Sensed, Geophysical, and Sample Datasets*, Lunar and Planetary Institute Workshop, Sept. 18–20, pp. 29–30.
- Jolliff B. L. (1997a) Clementine UV-VIS multispectral data and the Apollo 17 landing site: What can we tell and how well? *Lunar and Planetary Science XXVIII*, 671–672.
- Jolliff B. L. (1997b) High spatial resolution geochemistry and mineralogy of the Moon from Clementine multispectral data: The Taurus–Littrow Valley. *Geol. Soc. Am. Abstracts with Program* 29, A-215.
- Jolliff B. L. (1998b) A Clementine perspective of terra materials in the vicinity of the Apollo 17 landing site. *Lunar and Planetary Science XXIX*, #1850.
- Jolliff B. L., Korotev R. L., and Haskin L. A. (1998) The Apollo 17 central crater cluster and a new look at possible Tycho components in the soil. *Lunar and Planetary Science XXIX*, #1734.
- Jolliff B. L. and Haskin L. A. (1998) Integrated studies of impact-basin ejecta as probes of the lunar crust: Imbrium and Serenitatis. In *New Views of the Moon: Integrated Remotely Sensed, Geophysical, and Sample Datasets*, Lunar and Planetary Institute Workshop, Sept. 18–20, pp. 39–40.
- Wieczorek M. A., Haskin L. A., Korotev R. L., Jolliff B. L., and Phillips R. J. (1998) The Imbrium and Serenitatis basins: Impacts in an anomalous lunar province. In *New Views of the Moon: Integrated Remotely Sensed, Geophysical, and Sample Datasets*, Lunar and Planetary Institute Workshop, Sept. 18–20, pp. 95–96.